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CHARACTERISTICS OF WINTER CLIMATE IN FINLAND IN A WARMING WORLD

Anna Luomaranta

Department of Physics
Faculty of Science
University of Helsinki
Helsinki, Finland

ACADEMIC DISSERTATION in meteorology

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Author: Anna Luomaranta
Weather and Climate Change Impact Research
Finnish Meteorological Institute

Supervisors: Docent Kirsti Jylhä
Weather and Climate Change Impact Research
Finnish Meteorological Institute, Finland

Professor Heikki Järvinen
Department of Physics
University of Helsinki, Finland

Reviewers: Professor Egidijus Rimkus
Department of Hydrology and Climatology
Vilnius University, Lithuania

Dr. Mats A. Granskog
Centre for Ice, Climate and Ecosystems
Norwegian Polar Institute, Norway

Custos: Professor Heikki Järvinen
Department of Physics
University of Helsinki, Finland

Opponent: Professor Jukka Käyhkö
Department of Geography and Geology
University of Turku

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Author	ORCID iD
Anna Luomaranta	0000-0002-0891-7273

Title

Characteristics of winter climate in Finland in a warming world

Abstract

In northern countries, such as Finland, winter climate conditions affect the functionality of society in many ways. Due to the climate warming, the winter conditions are facing changes. Changes in snow and ice act as an indicator of the climate conditions in a region. The aim of this thesis is to examine what the winters are like in Finland in a changing climate.

The main results of this work are based on gridded observations, FMIClimGrid and E-OBS, and CMIP5 global climate model simulations. Using these, the observed snow, temperature and precipitation conditions in 1961-2014 were analyzed, and the future changes in Baltic Sea ice cover were projected for the ongoing century. In addition, two modeling studies were performed: The first assessed the performance of ECHAM5 atmospheric general circulation model in simulating snow melt timing in spring, and the second studied the ability of numerical convection-permitting weather prediction model HARMONIE to simulate a sea-effect snowfall case.

The results showed that, in Finland, the snow depth has decreased throughout the year and the snow season has shortened. Increasing liquid precipitation in winter was one of the main reasons for the changes. In spring, increasing air temperature has had an effect. The annual maximum sea ice extent and sea ice thickness in the Baltic Sea were projected to decrease during the ongoing century. However, the Baltic Sea is unlikely to become totally ice-free during typical winters in the coming decades.

When climate models are used to predict future climate conditions, it is essential that they describe the snow cover realistically, since it is an important element of the climate system. In the ECHAM5 climate model, Northern Eurasian snow melt timing was generally produced quite well when compared to satellite observations, but regional differences were also found. The reasons for the discrepancies turned out to be the simplifications in the calculations of the model's surface energy budget. The HARMONIE model also managed to simulate a known sea-effect snowfall case reasonably well. The simulation results improved when radar reflectivities were assimilated into the model.

As climate warming proceeds, the winter conditions will continue to change. The results of this thesis highlight the importance of continuous monitoring of climate conditions in the northern areas.

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Nimeke

Suomen talvi-ilmaston piirteitä lämpenevässä maailmassa

Tiivistelmä

Pohjoismaissa, joihin Suomikin kuuluu, talven ilmasto-olosuhteet vaikuttavat yhteiskunnan toimivuuteen monin tavoin. Ilmaston lämmetessä talviolosuhteet muuttuvat. Muutokset lumi- ja jääpeitteessä toimivat indikaattorina alueen ilmasto-oloista. Tämän väitöskirjan tavoitteena on tarkastella, millaisia Suomen talvet ovat muuttuvassa ilmastossa.

Väitöskirjan päätulokset perustuvat hilamuotoisiin havaintoaineistoihin, FMIClimGridiin ja E-OBS-aineistoon, sekä globaaleihin CMIP5-ilmastomallisimulaatioihin. Näistä aineistoista analysoitiin havaittuja lumi-, lämpötila- ja sadeolosuhteita jaksolla 1961-2014 sekä arvioitiin Itämeren jääpeitteen tulevia muutoksia vuoteen 2100 mennessä. Lisäksi työssä tehtiin kaksi mallinnustutkimusta: toisessa arvioitiin ECHAM5-ilmastomallin kykyä simuloida lumen sulannan ajankohtaa keväällä, ja toisessa tarkasteltiin säänennustusmalli HARMONIEN kykyä simuloida tunnettu rannikkolumisadetilanne.

Tulokset osoittivat, että lumensyvyys on Suomessa pienentynyt läpi vuoden ja lumikausi on lyhentynyt. Lisääntyneet talviaikaiset vesisateet olivat yksi pääsyy muutokseen. Keväällä myös lämpötilan nousu on vaikuttanut lumen vähenemiseen. Itämeren jääpeitteen vuotuisen maksimilaajuuden ja jäänpaksuuden arvioitiin pienentyvän kuluvalla vuosisadalla. On kuitenkin epätodennäköistä, että Itämeri muuttuisi kokonaan jäättömäksi tulevien vuosikymmenien tyypillisinä talvina.

Koska lumipeite on tärkeä osa ilmastojärjestelmää, on oleellista, että tulevaisuuden ilmasto-olosuhteita arvioivat ilmastomallit kuvaavat lumipeitteen realistisesti. ECHAM5-ilmastomalli kuvasi Pohjois-Euraasian lumensulannan ajankohdan yleisesti ottaen melko hyvin, mutta alueellisia eroja kuitenkin löytyi, kun tuloksia verrattiin satelliittihavaintoihin. Havaitut erot aiheutuivat yksinkertaistuksista ECHAM5-mallin maanpinnan säteilytaseen laskennassa. Myös HARMONIE-malli onnistui simuloimaan tunnetun rannikkolumisadetapauksen kohtuullisen hyvin. Simulaation tulokset paranivat, kun malliajoon lisättiin tutkahavainnot mukaan.

Kun ilmaston lämpeneminen etenee, talviolosuhteidenkin muutokset jatkuvat. Tämän väitöskirjan tulokset korostavat pohjoisten alueiden ilmasto-olosuhteiden jatkuvan seurannan tärkeyttä.

Julkaisijayksikkö

Sään ja ilmastonmuutoksen vaikutustutkimus

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Anna Luomaranta

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LIST OF ORIGINAL PUBLICATIONS

I **Luomaranta, A.**, Aalto, J. and Jylhä, K. (2019) Snow cover trends in Finland over 1961–2014 based on gridded snow depth observations, *International Journal of Climatology*, 39, 3147– 3159. https://doi.org/10.1002/joc.6007.

II Rasmus, S., Turunen, M., **Luomaranta**, A., Kivinen, S., Jylhä, K. and Räihä, J. (2020) Climate change and reindeer management in Finland: co-analysis of practitioners knowledge and meteorological data for better adaptation, *Science of the Total Environment*, 710, 136229, https://doi.org/10.1016/j.scitotenv.2019.136229.

III **Luomaranta, A.**, Ruosteenoja, K., Jylhä, K., Gregow, H., Haapala, J. and Laaksonen, A. (2014) Multimodel estimates of the changes in the Baltic Sea ice cover during the present century, *Tellus A*, 66, 22617, http://dx.doi.org/10.3402/tellusa.v66.22617.

IV Räisänen, P., **Luomaranta, A.**, Järvinen, H., Takala, M., Jylhä, K., Bulygina, O. N., Riihelä, A., Laaksonen, A., Koskinen, J., and Pulliainen, J. (2014) Evaluation of North Eurasian snow-off dates in the ECHAM5.4 atmospheric general circulation model, *Geoscientific Model Development*, 7, 3037-3057, https://doi.org/10.5194/gmd-7-3037-2014.

V Olsson, T., Post, P., Rannat, K., Keernik, H., Perttula, T., **Luomaranta, A.**, Jylhä, K., Kivi, R. and Voormansik, T. (2018) Sea-effect snowfall case in the Baltic Sea region analysed by reanalysis, remote sensing data and convection-permitting mesoscale modelling, *Geophysica*, 53(1), 65-91.

Author's contribution

The author was solely responsible for the summary of this thesis. In **Paper I**, the author was responsible for most of the data analysis and did all the writing with the help of the co-authors, excluding the beginning of chapter 2 (before 2.1). In **Paper II**, the author participated in analyzing the winter-related variables from the meteorological data and writing of chapters 2.3, 3 and 4. In **Paper III**, the author was responsible for all the calculations and data analysis except for those concerning the selection and evaluation of climate model simulations. The author participated in most of the writing excluding chapters 2.1.2 and 2.1.3. In **Paper IV**, the author participated in planning and analyzing part of the ECHAM5 simulations and satellite observations. The author participated in the writing of chapters 1, 2.1, 5.1 and 6. In **Paper V**, the author participated in analyzing the HARMONIE simulations.

LIST OF ACRONYMS

AIREP	Aircraft weather report
ALB1	Simulation with prescribed surface albedo
ALB1_NDG	Simulation with prescribed surface albedo and nudging
ALB2	Simulation with modified surface albedo parameterization
ALB2_NDG	Simulation with modified surface albedo parameterization and nudging
AMDAR	Aircraft based meteorological observation system
BEG	The beginning time of the seasonal snow cover period
BUOY	Buoy observations
CLARA-SAL	Data set of observed surface albedos
CMIP5,6	Coupled Model Intercomparison projects, phase 5 and 6
DJF	December, January, February
ECHAM5	Atmospheric general circulation model
ECMWF	European Center for Medium Range Weather Forecasts
E-OBS	Gridded climate data set for Europe
FDD-model	Freezing Degree-Day model
FMIClimGrid	Finnish Meteorological Institute gridded climate data for Finland
GCM	General circulation model
h	fast ice thickness
HARMONIE	High-resolution weather prediction model
ID	Ice days, Number of days when the daily maximum temperature is equal or less than 0°C
IFS	Integrated Forecast System, an operating global forecasting system
LAI	Leaf area index
MAXSN	Annual maximum snow depth
MIB	Annual maximum ice extent in the Baltic Sea

NDJFM	November, December, January, February, March
NF	Study domain in northern Finland
PILOT	Wind profiler observations
PR	Precipitation
PR_s	Solid precipitation
Rain-d	Rain days, Number of days when the daily precipitation is at least 1mm and the daily minimum temperature is at least 0 °C
RCP	Representative Concentration Pathway, a scenario that describes a possible greenhouse gas concentration trajectory
RCP4.5	Scenario with mid-range development in greenhouse gases
RCP8.5	Scenario with very high greenhouse gas concentrations
REF	Reference simulation
REF_NDG	Reference simulation which uses nudging
S	The annual cumulative (°C x d) sum of daily mean temperatures below 0 degrees (freezing degree-day sum)
SAI	Stem area index
SF	Study domain in southwestern Finland
SHIP	Sea-based stations
SOD	Snow-off date
SWE	Snow water equivalent
SYNOP	Surface synoptic observations
T	Temperature
TEMP	Radiosonde weather observations
TMAX	Maximum temperature
UTC	Coordinated Universal Time
ΔT	Temperature change

1. INTRODUCTION

Finland is a country of four seasons. Thermal winter, meaning the period of the year when the daily mean temperature stays below 0°C, is the longest season in a large part of Finland. (https://en.ilmatieteenlaitos.fi/seasons-in-finland). Due to the length of the winter, society needs to be well-informed of the prevailing cold-season climate conditions to understand the possible risks and benefits they may cause. If the prevailing conditions change, society needs to adapt to the changes.

Finland is located between a very maritime and a continental climate and also in the pathway of moving low pressure systems from the west, which makes the climate conditions variable. In winter, low pressure areas from the west typically bring moist and warmer air with precipitation to Finland. On the other hand, temperature can drop to very low degrees, if Arctic air masses from the north and east prevail. Also the Baltic Sea affects the weather and climate conditions especially near the coast areas. Depending on temperature, the winter precipitation falls as snow, sleet or rain.

Snow and sea ice are an essential part of winter climate in Finland. Snow and ice cover affect society and its inhabitants in many ways. Snow cover serves multiple recreation possibilities in winter time (Hall, 2014; Neuvonen et al., 2015) and protects vegetation from cold. It is also a storage of fresh water. On the other hand, snow may cause problems for transportation and electricity distribution (e.g. Andersson, 2010; Juga et al., 2014), and sea ice affects the shipping in wintertime (Critch et al., 2013). Furthermore, the amount and extent of snow and ice cover and changes in them are a sensitive indicator of climatic conditions in the region. Assessments of the possible changes in the sea ice cover and snow conditions will help societies to adapt to changes.

Finland is surrounded by the Baltic Sea from the south (Gulf of Finland), southwest (Archipelago Sea) and west (Gulf of Bothnia). It is common that these sea areas partly or totally freeze during winter, and the ice cover is present on average five months from December to April (Raateoja and Setälä, 2016). The ice cover in the Baltic Sea will face changes in response to global warming. A longer ice-free season of the Baltic Sea will again affect the climatic conditions of the surrounding regions. If a sea area remains ice-free in winter, it serves as a constant source of moisture and heat. If cold and dry air masses flow over the ice-free sea area, beneficial conditions for intensive convective snow bands to occur are generated. This sea-effect snowfall phenomenon is a typical part of Finland's winter climate. With certain wind directions, these snow showers may hit the coastline and cause problems to traffic, for example.

Objectives of this thesis

While global warming continues, it is the local effects that humans can perceive and that affect humans and society the most. This emphasizes the importance of local-scale climatological research. The main purpose of this thesis is to examine what the winters are like in Finland in the changing climate. This issue is addressed through the following questions:

- What changes have occurred in snow conditions and factors affecting them in Finland (**Papers I** and **II**)?
- What changes are expected to occur in sea ice conditions surrounding Finland (**Paper III**)?
- What factors affect climate model performance in simulating snow melt timing (**Paper IV**)?
- Based on a case study, how well can a sea-effect snowfall event be simulated over the Baltic Sea (**Paper V**)?

This thesis is organized as follows: In section 2, a review of snow- and ice-related climatological research is first given to put the results of this thesis in a broader context. In section 3, the approaches that were used in this thesis are introduced. Section 4 describes the observed conditions and changes in temperature, precipitation and snow cover in Finland and section 5 presents the future projections for Baltic Sea ice cover. In section 6, two examples of modeling studies benefiting climate research are presented. Finally, the results are summarized and discussed and the research questions are answered in section 7.

2. BACKGROUND

Warming due to the anthropogenic greenhouse effect is projected to be strongest in the northern areas of the Earth where also Finland is located. The observed and projected annual average temperature increase in the Arctic is assessed to be more than twice as strong as the global mean temperature increase (AMAP, 2019; Meredith et al., 2019). The warming in the north is largest in winter. Rising temperatures accelerate the melting of snow and ice, which has many direct and indirect impacts on the physical, chemical and biological systems in the Arctic area. The changes in the Arctic may also affect the conditions outside the region, for example through the changes in the atmospheric or ocean general circulation (AMAP, 2019; Meredith et al., 2019).

Snow and ice cover are the most important factors in the climate of the Northern Hemisphere and their presence in winter is typical at high latitudes. Snow and ice cover have a high albedo. Albedo is the fraction of solar radiation that is reflected from the surface. High albedo means that a large part of the incoming solar radiation is reflected back into space. This tends to cool the climate. When snow and ice decrease, surface albedo also decreases and a larger part of the incoming solar radiation is absorbed by the surface. This leads to warming which further reduces the ice and snow. Thus, this snow/ice-albedo feedback affects the energy budget of the Earth and highlights the significance of ice and snow cover in the climate system (Abram et al., 2019).

In several studies the recent past state and changes of the snow conditions have been reported at different spatial scales, ranging from the whole Northern Hemisphere (e.g. Brown and Mote, 2009; Choi et al., 2010; Park et al., 2012; Callaghan et al., 2012; Vaughan et al., 2013; Hernández-Henríquez et al., 2014; Mioduszewski et al., 2015; Derksen et al., 2016) or Eurasia (Bulygina et al., 2011; Ye and Cohen, 2013; Zhong et al. 2018) to individual countries or smaller districts within them (e.g. Kohler et al., 2006; Brown, 2010; Skaugen et al., 2012; Kerr et al., 2013; Stuefer et al., 2013; Najafi et al., 2016). The magnitude of the changes has not been spatially uniform in the Northern Hemisphere. For example, the changes in snow depth have differed between North America and Eurasia: an increase in snow depth in many regions over Eurasia was observed during the period 1966-2009, while in North America decreasing snow depth trends occurred (Bulygina et al., 2011, Callaghan et al., 2012). On the other hand, updated trends in maximum snow depth over Russia in 1966-2014 show less evidence of significant increases compared to trends reported by Bulygina et al. (2011) (AMAP, 2017). Also Park et al. (2012) reported wide-spread negative snow depth trends in most of pan-Arctic after about 1990, clear positive trends occurring only in Western Siberia. Within Eurasia, the changes in snow conditions vary substantially depending on the latitude, elevation and the proximity to the sea. The largest decreases in snow water equivalent (SWE) and snow cover duration in recent decades have occurred in maritime regions in northern Scandinavia and the Pacific coast region of Russia (Callaghan et al., 2012).

Two main factors which affect snow conditions are temperature and precipitation (e.g. Räisänen, 2008; Brown and Mote, 2009; Mankin and Diffenbaugh, 2015; Mudryk et al., 2016). Temperature defines the form of precipitation, which affects the amount of snow on the ground. Besides altering the amount and form of precipitation, increasing temperatures also affect the snow cover by either increasing or decreasing the number of thaw days, the sign of the change depending on the prevailing baseline mean temperatures. In the late 20th century, the borderline between increasing and decreasing snow water equivalent (SWE) was found to have mainly corresponded to the -20°C isotherm of the cold season (NDJFM) mean temperature (Räisänen, 2008). The midlatitude snow margin zone was the most sensitive region for snow loss due to warming in 1981-2010 (Mudryk et al., 2016). Mankin and Diffenbaugh (2015) found that in 8 out of 9 of their study regions in the Northern Hemisphere near-future March snow accumulation trends responded negatively to temperature increases and all their study regions exhibited reductions in the fraction of precipitation falling as snow. However, internal variability can influence the magnitude of snow accumulation trends. Brown and Mote (2009) noted that, among various snow variables, snow cover duration has the strongest sensitivity to warming. They discovered that the largest decreases in Northern Hemisphere snow cover duration in 1966-2007 were located in a zone where the mean air temperature of the snow season varied from -5 to +5 degrees Celsius.

Climate model results project that drastic changes in snow conditions are expected to continue during the ongoing century (Bintanja and Andry, 2017). Mid-winter SWE and maximum SWE are projected to increase in the coldest regions of the Northern Hemisphere (Räisänen, 2008; Callaghan et al., 2012; AMAP, 2017), elsewhere SWE is expected to decrease. In spite of the projected increases in SWE in the coldest regions, snow season is expected to shorten at both ends in the whole Northern Hemisphere (Räisänen, 2008; Callaghan et al., 2012; AMAP, 2017). In Europe, the largest percentage reductions in the number of snow cover days and the average SWE are projected to occur in southern and western Europe (Jylhä et al., 2008). In Northern Fennoscandia, the annual number of snow cover days is projected to decrease most in the coastal regions and least in the mountainous areas (Lehtonen et al., 2013). In Northern Europe, the regional and interannual variability is projected to remain high: individual snow-rich winters can still occur in the future decades even where the long-term mean SWE is projected to decrease (Räisänen and Eklund, 2012). Snowfall is also projected to decrease across much of the Northern Hemisphere in the 21st century, the transition between negative and positive seasonal and annual trends occurring close to the corresponding average -10°C isotherms over the period 1986-2005 (Krasting et al., 2013). At the same time, rainfall is projected to increase throughout the year (Bintanja and Andry, 2017). In midwinter in the coldest regions, snowfall is still projected to increase (Räisänen and Eklund, 2012; Räisänen, 2015; Danco et al., 2016; Krasting et al., 2016) but the snowfall fraction is expected to decrease due to increasing rainfall (Bintanja and Andry, 2017). When using climate model data, it is important to realize that climate models have deficiencies and the model physics include simplifications and parametrizations. For example, many different processes affect the snow conditions in a climate model and improving a single process may either improve or deteriorate the agreement with observations.

Arctic sea ice extent has decreased since 1979 in each month (Meredith et al., 2019). The decrease has been largest in summer and smallest in winter. The loss of sea ice on a more regional scale is seen also in the Baltic Sea, which is a small inland sea bordering Finland in the south and west. Annual maximum ice extent in the Baltic Sea (MIB) has been monitored fairly accurately from 1880 onwards (Haapala et al., 2015). A large interannual variability is typical for the annual maximum ice extent. Still, a significant decreasing trend in MIB (-3400 km^2/decade or -2%/decade) has been observed for the past 100 years (1912-2011) (Haapala et al., 2015). In addition, a decreasing trend in the length of the ice season in the Finnish coastal zone has been observed (Ronkainen, 2013). In the Bothnian Bay (Kemi), the trend was -18 days/100 years and in the eastern Gulf of Finland (Loviisa) -41 days/100 years.

The decline of the Arctic sea ice is projected to continue through the ongoing century, but there is a large spread in the climate model results concerning the timing of when the Arctic may become ice-free in the summer (Meredith et al., 2019). Also the Baltic Sea ice will continue to face changes. Höglund et al. (2017) used a coupled ice-ocean model system with two global climate models and two scenarios to predict the future changes in the ice conditions of the Baltic Sea. According to their results, the annual maximum ice extent will decrease 46-57% under the RCP4.5 scenario, which describes a mid-range development in greenhouse gas concentrations, and 81-82% under a very high greenhouse gas scenario, RCP8.5, by the end of the century. Also the ice thickness and the length of the ice season were projected to decrease. The decrease in the ice extent and thickness can lead to increased ice mobility and thus more ridging events.

3. APPROACHES FOR STUDYING COLD CLIMATE FEATURES

The specific topics and materials used in this thesis are presented in Fig. 1. Several different data sets and approaches were used. Data sets consisted of observations and model-based data and they were used together or separately with different methods to gain information of observed winter climate conditions and future projections of sea ice. Observations and model-based data were both utilized also in two modeling studies concerning climate model performance in snow-melt timing and a sea-effect snowfall event. In this chapter, the different data sets are first introduced and then the methods are presented. Lastly, two numerical modeling experiments are described.

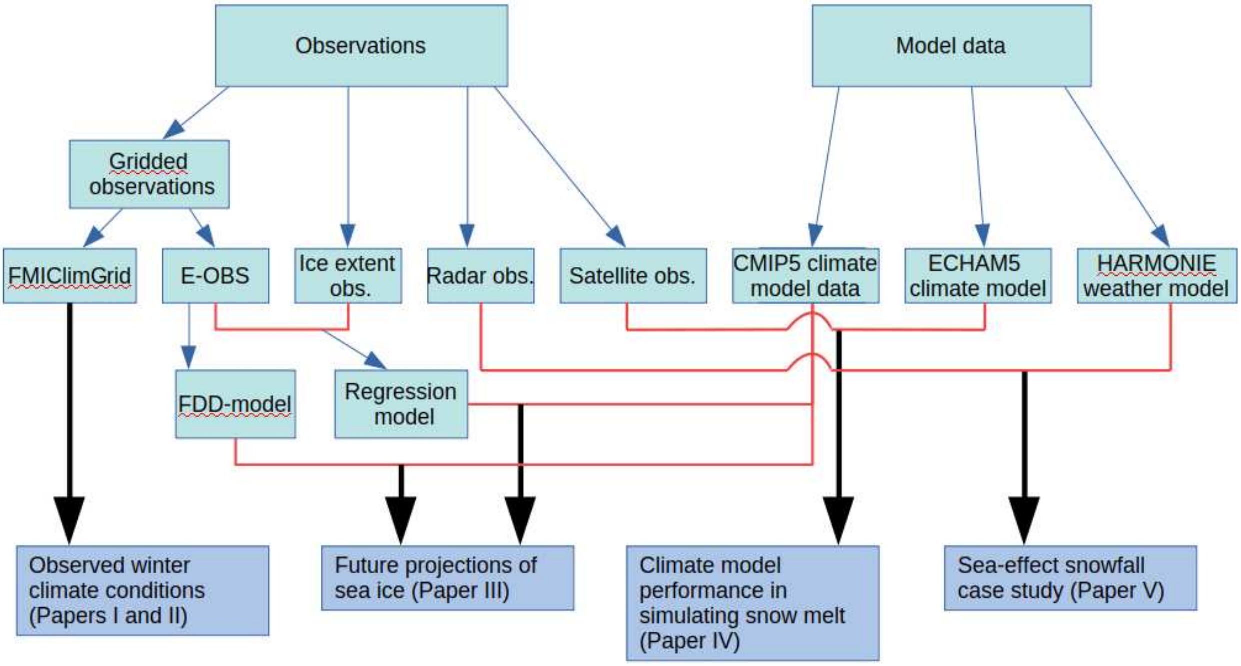

Figure 1. Flow diagram showing the main topics and materials of the thesis.

3.1 Data

3.1.1 Gridded datasets based on in situ -observations

Weather observations are made all around the world. Station observations tell us about the weather conditions only at a certain station and its direct vicinity. To get a more comprehensive picture of conditions and changes, gridded datasets are an advantageous approach for analysis.

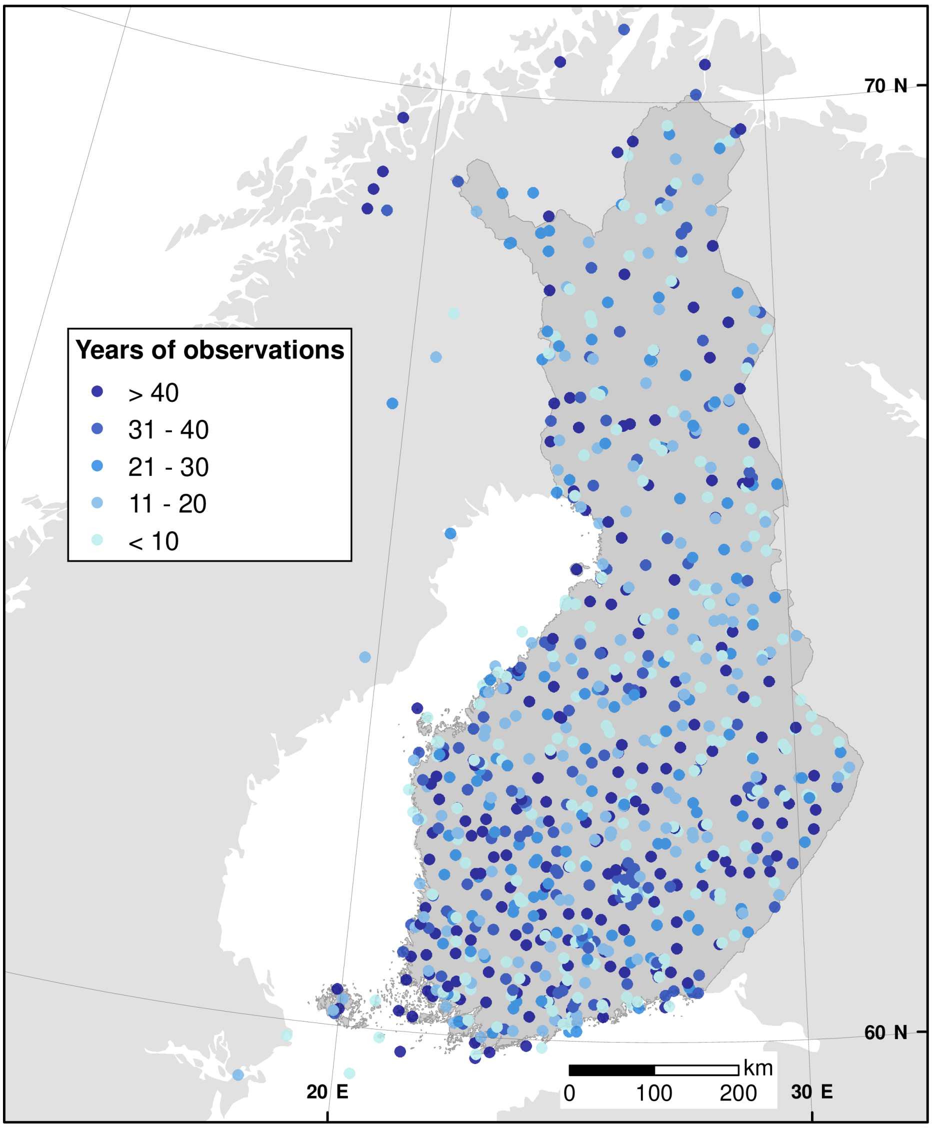

*Figure 2. The station network that was used for producing gridded snow depth data. The points denote the stations in Finland and in neighboring countries. The colors indicate the total numbers of years with snow depth observations. (Reproduced from Fig. 1 of **Paper I**.).*

The past conditions and changes in temperature, precipitation and snow cover were assessed using the daily gridded climate data for Finland (FMIClimGrid, version 1.0, Aalto et al. 2016). In this data set, meteorological station data is interpolated to a 10 km x 10 km grid, which covers whole Finland. The gridding of the station observations was produced with kriging interpolation (Matheron, 1963; Goovaerts, 2000). The background information for the interpolation took into account the geographical locations of the stations, topography and the effects of water bodies. In Fig. 2, the station network used for producing gridded snow depth data is shown. In **Paper I**, precipitation, temperature and snow depth, and variables related to them, were examined. These were analyzed from FMIClimGrid data for the years 1961-2014 for the whole of Finland. In **Paper II**, we examined these variables for the shorter time range of 1981-2010 and a smaller study region which covered the reindeer management area in Finland.

In **Paper III**, we used E-OBS daily gridded dataset version 6.0 for the years 1951-1960 and version 7.0 for the years 1961-2012 (Haylock et al., 2008) together with observed values of annual maximum ice extent in the Baltic Sea (MIB) for the years 1951-2012. E-OBS gridded dataset is a dataset which covers Europe in a 0.1 or 0.25 degree grid. It includes temperature, precipitation and sea level pressure on land areas. In this work, we utilized data with a resolution of 0.25 degrees.

3.1.2 Climate model data

Future climate changes are assessed using climate models. **Paper III** used the air temperature data of simulations from 28 CMIP5 global climate models in projecting the future changes in the Baltic Sea ice cover. These simulations were under two greenhouse gas scenarios: RCP4.5 and RCP8.5 (Moss et al. 2010, van Vuuren et al. 2011). The former represents mid-range development in greenhouse gas concentrations and the latter represents very high greenhouse gas concentrations. The differences between the scenarios are small at the beginning of our study period, but increase over time.

Monthly mean temperature data for both scenarios were available for a total of 35 climate models. However, we excluded those models from the analysis that failed to meet three fundamental conditions. First, the simulated global mean temperature trend during the past 50 years was not allowed to exceed the observation-based estimate by more than 0.4°C. Second, the projected global mean temperature increase under the various RCP scenarios was not allowed to behave inconsistently, meaning that for an individual model the ratio of temperature responses to e.g., RCP8.5 and RCP4.5 scenarios was not permitted to notably differ from the multimodel median of that ratio. Third, the simulated baseline-period climatological mean temperature and/or precipitation in Europe was not allowed to deviate markedly from the observations. Fulfilling these conditions led to the exclusion of seven models from the analysis.

The climate model data were smoothed by applying a 30 yr running mean and interpolated onto the same 0.25° grid as in E-OBS gridded dataset.

3.1.3 Other observations

Besides the gridded data, which was introduced in section 3.1.1, several other observation-based data sets were utilized in this work as reference material.

Observations of the annual maximum ice extent of the Baltic Sea (MIB) were used in **Paper III**. MIB is the most widely used parameter to indicate climate variability in the Baltic Sea region. Its recordings date back to 1720 (Seinä and Palosuo, 1996), but the most reliable observations begin in the late 19th century (Vihma and Haapala, 2009). We used MIB observations from the years 1952-2012. Furthermore, observations of the annual maximum ice thickness available for Kemi (63.73°N, 24.55°E) and Loviisa (60.42°N, 26.27°E) in 1971-2000 (Jevrejeva et al., 2002) were also used in **Paper III**.

2 m air temperature observations from Climate Research Unit (CRU) land surface air temperature data, v. 3 (CRUTEM3; Brohan et al. 2006) was employed in **Paper IV** as well as monthly mean surface albedo from the CLARA-SAL data set (Riihelä et al., 2013). Also satellite observations of snow melt timing over Northern Eurasia (Takala et al. 2009) were utilized in **Paper IV**.

Weather radar observations from Finland was used in **Paper V** as reference material for a sea-effect snowfall modeling study with weather prediction model HARMONIE (see Chapter 3.3.2).

3.2 Methods

3.2.1 Analyzing temporal averages and trends from the FMIClimGrid data

The following averages and trends of snow-related quantities were analyzed from FMIClimGrid data for the period 1961-2014 in **Paper I**:

- Monthly mean snow depth calculated from daily values.
- Annual maximum snow depth.
- The beginning time of the seasonal snow cover period (BEG): the first day after the autumn's last snow-free day when the snow depth reaches at least 1 cm.
- Snow-off date (SOD): the first snow-free day in spring after the winter's maximum snow depth. The maximum snow depth was assumed to occur after January 1st.

For two shorter time periods (1961-1987 and 1988-2014) and two smaller study domains, we also examined temperature- and precipitation-related quantities and the role of these in controlling snow depth (**Paper I**). These study domains represent two contrasting snow climate regimes within Finland: a southwestern maritime region (SF) and a northern region with Arctic conditions (NF). These quantities included:

- Monthly mean temperature (T): temperature affects the form of precipitation and melting of snow.
- Monthly mean amount of precipitation (PR): precipitation may increase or decrease the snow amount depending on its form.
- Monthly mean maximum temperature (TMAX).
- Monthly mean amount of solid precipitation (PR_s): precipitation falling on a day when daily maximum temperature is equal to or less than 0°C.

The significance of the change in these quantities over the two time periods was assessed for each month and winter period (DJF) using two-sided Mann-Whitney-tests.

For the shorter time period of 1981-2010 we analyzed averages, trends and standard deviations of following quantities in autumn, winter and spring for the reindeer management area in Finland (**Paper II**):

- Ice days (ID): Number of days when the daily maximum temperature is equal to or less than 0°C.
- Rain days (Rain-d): Number of days when the daily precipitation is at least 1 mm and the daily minimum temperature is at least 0°C.
- Annual maximum snow depth (MAXSN).
- The beginning time of the seasonal snow cover period (BEG).
- Snow-off date (SOD).

3.2.2 Regression model for predicting sea ice extent

E-OBS data and observations of the maximum ice extent in the Baltic Sea (Fig. 1) were combined to form a simple non-linear regression model, following Tinz (1996) and Jylhä et al. (2008). This model was then used with CMIP5 data to predict the future sea ice conditions. The regression equation was given by:

$$MIB = A e^{-BT} \quad (1)$$

where MIB is the annual maximum ice extent (km^2) and T is the November-March mean temperature (°C) averaged over the coastal grid points around the Baltic Sea. Based on the data (Fig. 3), the following values were derived for the coefficients: A= $(90.2 \pm 4.2) \times 10^3$ km^2 and B = (0.253 ± 0.015) $°C^{-1}$.

The regression model was used with E-OBS and CMIP5 climate model data to project the future changes in the annual maximum ice extent in the Baltic Sea. For assessing the future temperature, a simple delta-change method was used. We first calculated the change in November-March mean temperature, ΔT, at coastal grid points between the baseline period 1971-2000 and each of the seven future decades in the period 2021-2090 using CMIP5 air temperature. ΔT for each decade was calculated as a 30 yr mean, centered on that decade. For example, mean T in 2011-2040 represents the decade 2021-2030. These temperature increases for each future decade were added to the observed E-OBS mean temperature values in 1961-2010 (50 values) to create an artificial temperature distribution for each future decade. Next, these samples of T were used in Eq. 1 to obtain the frequency distribution of MIB for each of the future decades. The uncertainty in the results was assessed by performing the calculations for each climate model and for both RCP scenarios. Also the 28-model average temperature was used in calculations to get a best estimate for the long-term trends. The model uncertainty assessment focused on the decade 2041-2050.

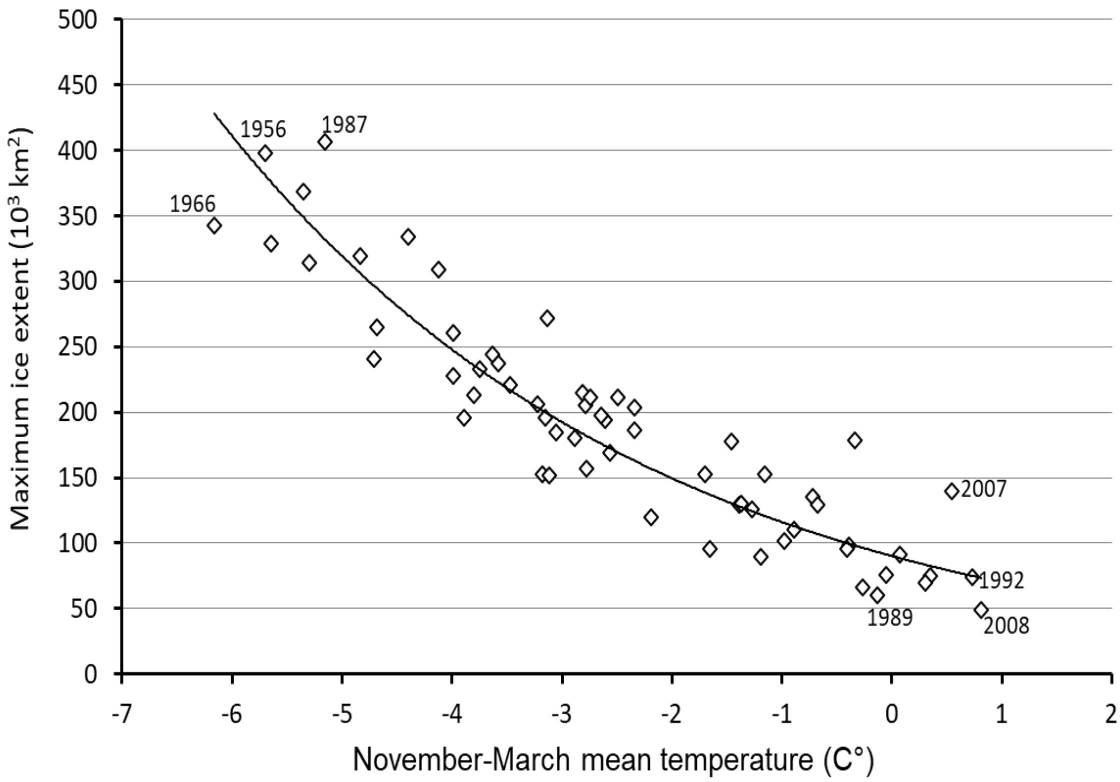

*Figure 3. The regression model for the ice extent in the Baltic Sea. The model was fitted to the observed annual maximum sea ice extent and the November-March mean temperature in coastal grid points in 1951-2012. (Reproduced from Fig. 4 of **Paper III**.)*

3.2.3 FDD-model for sea ice thickness

The 30 yr mean of the annual maximum fast ice thickness, h, was calculated using an analytical solution for the thermodynamic ice growth equation that is based on the sum of freezing-degree days (Stefan, 1891; Zubov, 1945; Leppäranta, 1993), so-called FDD-model (**Paper III**):

$$h = \sqrt{a^2 S + d^2} - d \quad (2)$$

where S = the annual cumulative (°C x d) sum of daily mean temperatures below 0 degrees (freezing degree-day sum), a = 3 cm(°C x d)$^{-1/2}$, d = 10 cm.

The sum of the freezing-degree days for future decades, that was needed in Eq. 2, was calculated from air temperature output data from the CMIP5 simulations. The changes in 30 yr monthly mean temperatures in coastal grid points, ΔT, for each decade in 2021-2090, were added to the observed 30 yr monthly mean temperatures in 1971-2010 derived from E-OBS. The sum of the freezing-degree days was obtained from monthly mean temperatures of each decade as follows: the negative monthly mean temperatures were multiplied by the number of days in the month. Then the sum of the contributions of all months with negative mean temperature was used in Eq. 2. These calculations were performed separately for temperatures of each CMIP5 model and for the 28-model mean.

Equation (2) does not take into account the snow layer lying on top of the ice cover. Ice thicknesses are thus systematically overestimated by up to 40 cm. The ice thickness calculated using (2) can be considered as the upper limit for the ice growth in a typical winter (Leppäranta, 1993). As the E-OBS gridded temperatures cover only land areas, the ice thickness could only be assessed in the coastal areas.

3.3 Numerical model experiments

3.3.1 ECHAM5 simulations

As the snow cover has both global and local climatic impacts, it is essential that climate models that are used to project future climate, produce the observed distribution of snow cover realistically. **Paper IV** examined the ability of ECHAM5.4 atmospheric general circulation model (GCM) to simulate the Northern Eurasian snow melt timing in 1979-2006 as an example of climate models. The model was used in resolution T63 which corresponds to a grid spacing of 1.875 degrees (Roeckner et al., 2003, 2006).

In ECHAM5's snow scheme, snow water equivalent (SWE) is a prognostic variable, but changes in snow density or grain size are not taken into account in the snow-related model physics. In the model, SWE intercepted by the canopy (Roesch et al. 2001) and SWE on the ground (Roeckner et al. 2003) are calculated separately. The grid-mean surface albedo, which is closely related to the snow cover, is parameterized and it depends on the specified background albedo, the fractional forest area of the grid cell, the snow cover on the canopy, the snow cover on the ground and a specified snow albedo. The albedo of snow on land depends on the surface temperature and the albedo of snow-covered forests depends on the leaf-area index (LAI). A complete description of the parameterization is found in Roeckner et al. (2003).

First, a reference experiment (REF) was run using the default version of ECHAM5.4 in an ordinary climate simulation mode. The experiment was conducted for years 1978-2006 and all but the first year were used for analysis of the results. The snow-off date was evaluated in the experiment results based on daily mean SWE values. The snow-off date was defined to be the first day with zero SWE after a winter's maximum SWE. This definition is the same as was used for SOD in **Paper I** and **II**, except that in these **Papers** SOD was calculated using snow depth instead of SWE. The results from the REF experiment were compared to satellite observations of SOD and differences between these were found. In order to explain the discrepancies, we performed five more ECHAM5 experiments, where the model's surface albedo and/or atmospheric circulation was modified.

All six experiments used observed sea surface temperatures and sea ice (AMIP Project Office, 1996) as boundary condition and the concentrations of well-mixed greenhouse gases were held constant following AMIP II guidelines (AMIP Project Office, 1996). As surface albedo strongly influences the energy available for melting snow in spring, in two of the experiments, ALB1 and ALB2, the reduction of the biases in ECHAM5's surface albedo was attempted by modifying the model's surface albedo field. In experiment ALB1, the model's albedo field over continents was replaced by prescribed surface albedos based on observations (CLARA-SAL, Riihelä et al., 2013). In ALB2, two modifications were implemented in ECHAM5's surface albedo parameterization. First, the minimum snow albedo value was increased from 0.3 to 0.6. Second, a stem area index (SAI=2) was added to the equation which is used for calculating the albedo of snow-covered forests, as it was noted by Roesch and Roeckner (2006) that the shadowing of the ground below the canopy by stems and branches was neglected in ECHAM5.

The remaining three experiments (REF_NDG, ALB1_NDG, ALB2_NDG) were primarily similar to the other three experiments (REF, ALB1 and ALB2), except that so-called nudging was used in all of them. In these nudging experiments four model fields were nudged towards ERA-Interim reanalysis data (Dee et al., 2011): vorticity, divergence, atmospheric temperature and logarithm of surface pressure. The nudging acts to minimize the errors in simulated atmospheric circulation, which is one possible cause for differences between simulated and observed snow-off dates.

3.3.2 HARMONIE simulations

Winter climate in Finland includes many small-scale weather events. One such is the so-called sea-effect snowfall phenomenon which is a common occurrence in sea areas around Finland in winter. **Paper V** examines the use of a high-resolution numerical weather prediction model, HARMONIE, together with other datasets for investigating the basic characteristics of a sea-effect snowfall case.

HARMONIE is a numerical convection-permitting mesoscale model (Bénard et al., 2010, Brousseau et al., 2011). In this kind of high-resolution models, the small-scale convective phenomena can be resolved and convection parameterization schemes are no longer needed. This is advantageous, as parameterization of convection is a large source of error and uncertainty in lower-resolution models (Prein et al., 2015, Weusthoff et al., 2010).

In our model setup, model version 40h1.1 was used and the model resolution was 2.5 km. The simulation domain covered Finland, Scandinavia and the Baltic countries. The boundary conditions were obtained from the Integrated Forecast System (IFS), which is an operational global forecasting system at ECMWF. The boundary conditions were updated every hour. Data assimilation is used in HARMONIE meaning that a running model simulation is corrected at regular time intervals with observations. The basic set of observations consisted of surface synoptic observations (SYNOP), sea-based stations (SHIP), aircraft reports

(AMDAR, AIREP), buoy observations (BUOY), radiosondes (TEMP) and wind profiler (PILOT) observations.

We ran two experiments with the HARMONIE model to simulate the selected sea-effect snowfall case. In the reference simulation, the above-mentioned basic set of observations was assimilated to the model. In the second simulation also radar reflectivities were utilised. The purpose was to examine if the assimilation of the radar reflectivities improves the simulation results. Both of the simulations consisted of several forecast cycles. We also qualitatively evaluated which cycle gave the best results compared to radar observations. The results from HARMONIE simulations were also compared to some other observational data in **Paper V**, but the focus in this thesis is on the HARMONIE model and its results.

4. OBSERVED WINTER CLIMATE CONDITIONS IN FINLAND

4.1 Temperature and precipitation

Temperature and precipitation are the main variables affecting snow conditions and other winter climate characteristics in Finland. In **Paper I**, changes in these were examined at monthly scale in two smaller domains (boxes in Fig. 6) between periods 1961-1987 and 1988-2014. These domains represented two contrasting snow climate regimes within Finland: SF in the southwestern maritime region and NF in the northern region with Arctic conditions. In **Paper I**, we also studied the changes in solid precipitation. The amount of solid precipitation was assessed so that the total precipitation falling on a day when the maximum temperature was less than or equal to zero degrees Celsius was classified as solid precipitation. Our findings indicated that in SF, both the monthly mean and monthly maximum temperatures (T and TMAX) increased in January-April and total precipitation increased in January and February (Fig. 4). In SF, the amount of solid precipitation did not change but the fraction of solid precipitation decreased in January and February meaning that the increase in total precipitation was due to increases in mixed and liquid precipitation.

In NF, T and TMAX increased in some winter and spring months, but because of the colder baseline climate they stayed below zero also during the latter period (Fig. 5). Solid precipitation was found to increase when the three months' sum over the winter months, December-February (DJF), was examined. Also total precipitation and mixed and liquid precipitation were found to increase when they were calculated over the DJF period. The changes in the annual amount of solid precipitation divided Finland into two parts (Fig. 6.). In northern and eastern Finland, solid precipitation increased in 1961-2014 whereas in southern and western Finland it decreased.

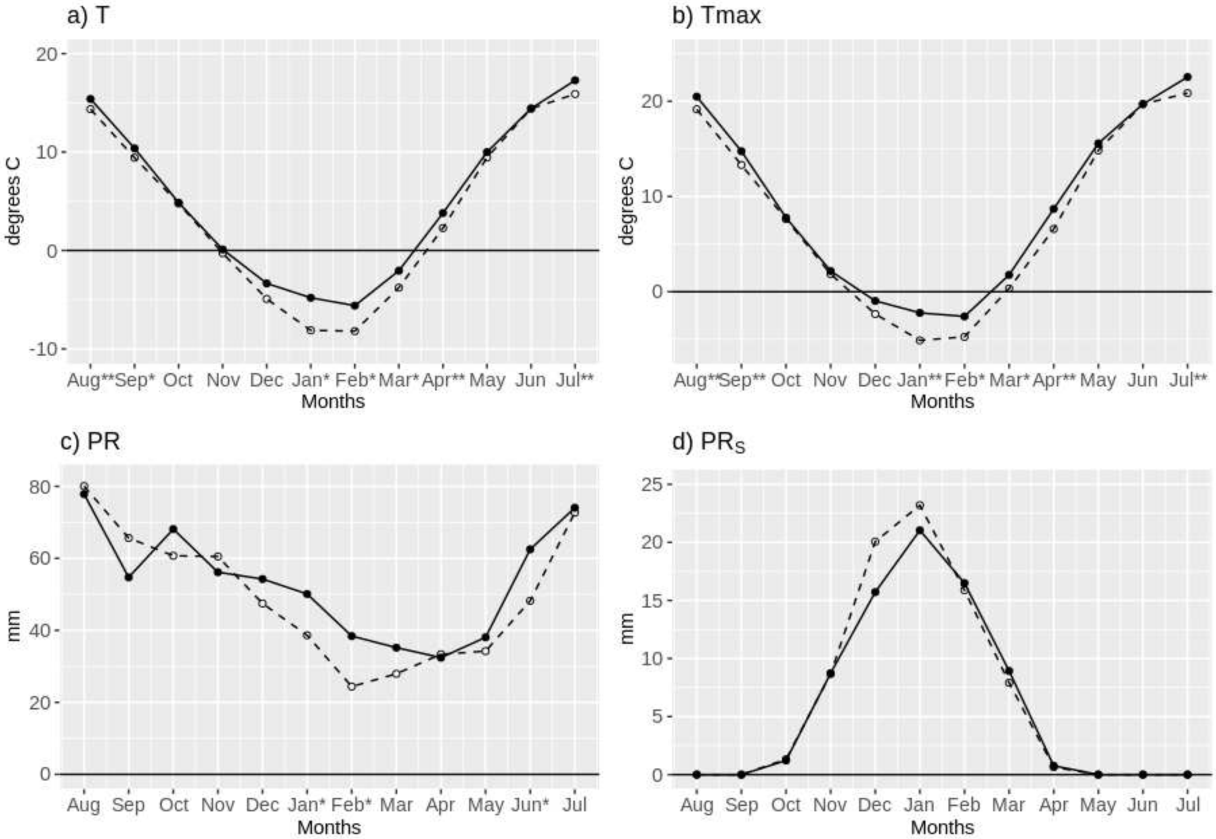

*Figure 4. Twenty-seven-year mean seasonal cycles of monthly mean temperature (a,T), monthly maximum temperature (b, TMAX), monthly mean amount of precipitation (c, PR) and monthly mean solid precipitation (d, PR_s) in southern Finland (SF). The dashed line indicates the 1961-1987 period and the solid line indicates the 1988-2014 period. The months when the change between the two periods is statistically significant at the 5% level and 1% level according to two-sided Mann-Whitney tests are denoted by * and **, respectively. (Reproduced from Fig. 4 of **Paper I**.)*

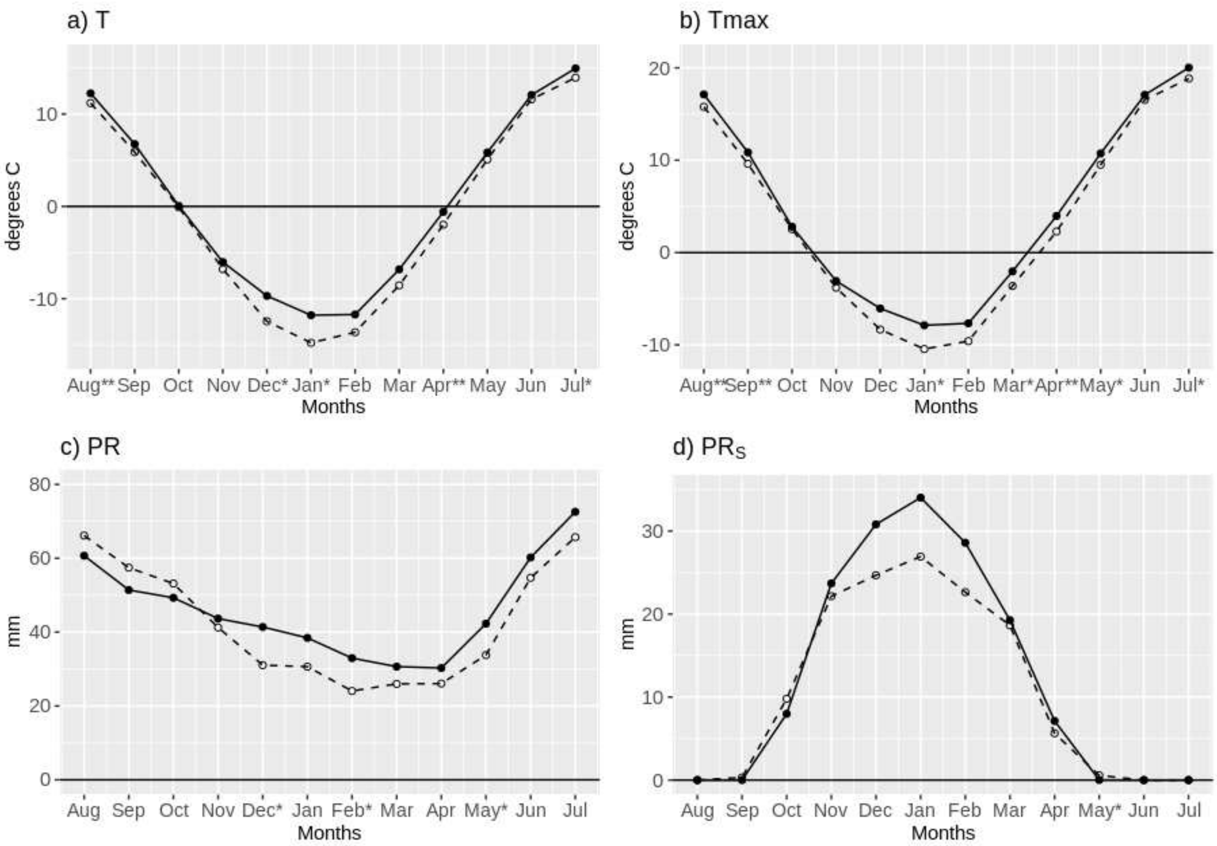

*Figure 5. As in Fig. 4 but for northern Finland (NF). (Reproduced from Fig. 5 of **Paper I**.)*

In **Paper II**, changes in rain days and ice days were examined in autumn, winter and spring in 1981-2010. A rain day was defined to be a day when the minimum temperature was above or equal to zero and daily precipitation amount was at least 1 mm. An ice day was defined to be a day when the maximum temperature was 0 degrees at the highest. Slight local statistically significant increases in the number of rain days in winter in the southern part of the reindeer management area were found in 1981-2010. There was no clear trend in the number of ice days in autumn or winter. In spring, the number of ice days was declining in the northwestern areas of the reindeer management area (Fig. 7.), locally 3-5 days/decade. The standard deviation of ID in these regions was 0.5-3 days. In spring, the rain days were found to slightly increase, especially in the southern parts of the reindeer management area. This trend was 2-3 days/decade and the corresponding standard deviation was 3-5 days in these areas.

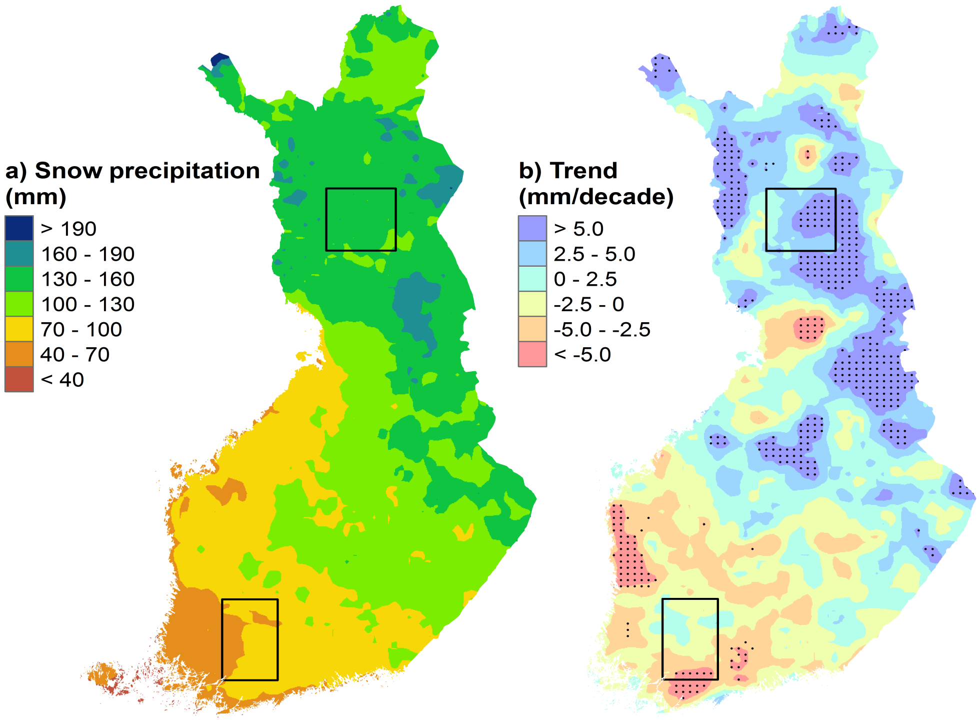

Figure 6. a) The mean annual snowfall in 1961-2014, b) The linear trend in annual snowfall in 1961-2014. Black dots mark the regions with a statistically significant trend at the 5% level. The boxes denote the domains of SF and NF. (Reproduced from Fig. 6 of ***Paper I****.)*

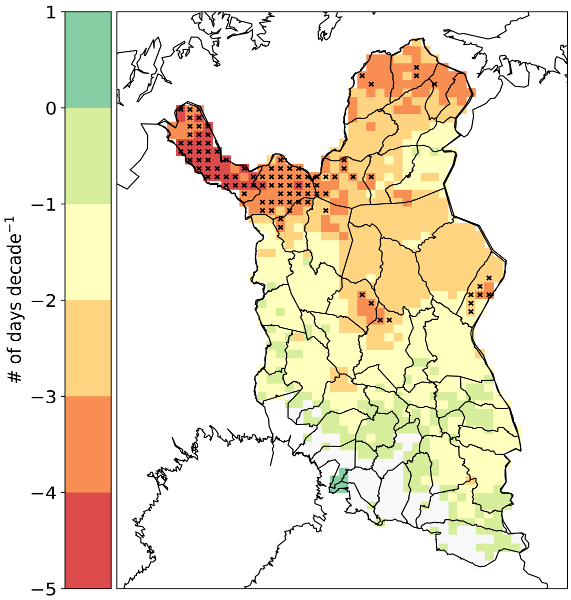

Figure 7. The linear trend in ice days (ID) in spring in 1981-2010 in the reindeer management area in Finland. The regions with statistically significant trend at the 5% level are marked with x. (Reproduced from Fig. 11 of ***Paper II****.)*

4.2 Snow depth and snow cover season

In **Paper I**, the changes in snow cover in Finland were analyzed for the years 1961-2014 from the FMIClimGrid data. In a typical winter in Finland in 1961-2014, snow depth gradually increased towards March. The snow depth values were the highest in northern Lapland and the lowest in southwestern Finland. The long-term trends in monthly mean snow depth were generally negative during the study period. The strongest absolute decrease, locally up to 4-6 cm/decade, occurred in February and in March in southern and western Finland and in April in central Finland. Annual maximum snow depth (MAXSN) decreased most in southwestern Finland – in places more than 4 cm/decade (Fig. 8). The trend in MAXSN was compared to the trend in the annual solid precipitation (Fig. 6). The spatial pattern correlation between these showed that in almost half of Finland's area MAXSN decreased despite increasing solid precipitation. In **Paper II**, MAXSN was analyzed for the shorter period of 1981-2010 and only for the reindeer management area. In this area and period, MAXSN showed a statistically significant decreasing trend of 5-10 cm/decade in the northern part of the reindeer management area and the standard deviation was 10-20 cm in the same region.

In 1961-2014, the seasonal snow cover period typically began in northern Finland before the end of October and in southwestern Finland at the end of December (Fig. 8). The seasonal snow cover period ended in southwestern Finland as early as the end of March, whereas in northern Finland, at the end of May. These beginning and end dates of the seasonal snow cover period (BEG and SOD) changed almost everywhere in Finland – BEG to later dates and SOD to earlier dates. The strongest change in BEG occurred in the central and southeastern parts of Finland, locally more than 4 days/decade, and the strongest change in SOD was found in the western coastal areas, locally more than -4 days/decade. The length of the seasonal snow cover period shortened practically everywhere in Finland. In **Paper II**, BEG and SOD were analyzed for the shorter period of 1981-2010 and only for the reindeer management area. During this period, there was a tendency towards later BEG, but this trend was significant only in the most northern regions. SOD had a significant decreasing trend only in the southern part of the reindeer management area, locally 3-5 days/decade.

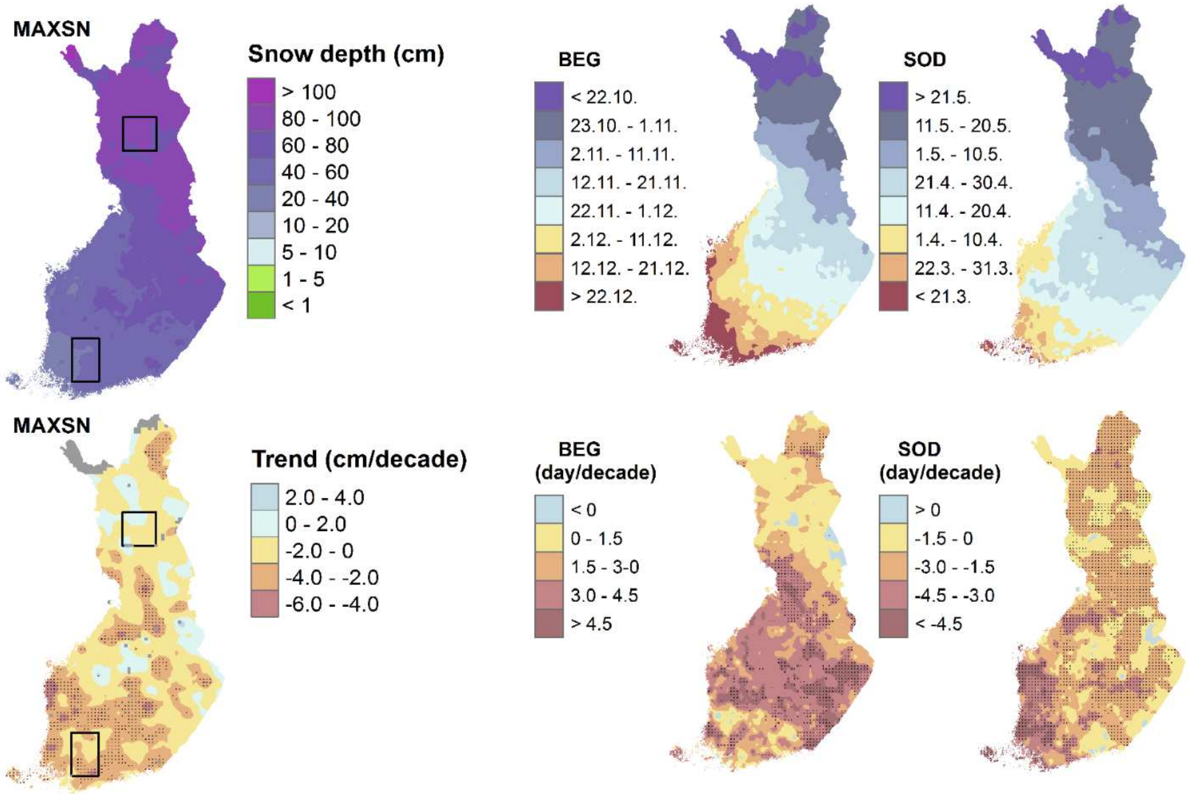

*Figure 8. Upper row: The mean annual maximum snow depth (MAXSN), the average beginning (BEG) and end date (SOD) of seasonal snow cover period in 1961-2014. Lower row: The linear trends of MAXSN, BEG and SOD in 1961-2014. The small black dots denote the regions where the trend is statistically significant at the 5% level. (Reproduced from Figs. 2 and 3 of **Paper I**.)*

5. PROJECTED CHANGES IN THE SEA ICE IN THE BALTIC SEA

5.1 Annual maximum ice extent in the Baltic Sea

Maximum ice extent (MIB) is the most widely used parameter to indicate climate variability in the Baltic sea region. Traditionally ice winters in the Baltic Sea have been sorted into ice severity classes on the basis of the observations of the annual maximum ice extent. According to the present standards (Vainio, 2011), winters with an ice extent smaller than 115×10^3 km^2 are classified as mild, those from 115 to 230×10^3 km^2 as average and those from 230 to 345×10^3 km^2 as severe. If the ice extent exceeds 345×10^3 km^2, it is classified as extremely severe.

In **Paper III**, we projected future changes in the Baltic Sea ice cover with a regression model using air temperature. The changes in annual maximum fast ice thickness (MIB), based on the ensemble mean of 28 models, were calculated for three percentiles: the median, and 5th and 95th percentiles. During the period 2021-2090, the linear trends for all percentiles under both scenarios, RCP4.5 and RCP8.5, were decreasing (Fig. 9). The 95th percentile, which represented an uncommonly wide ice cover, was projected to diminish faster than the median or the 5th percentile under both scenarios. If RCP8.5 is realized, according to our results the average ice winters would be very exceptional from the 2060s onward. Under RCP4.5, the 95th percentile falls to the category of average ice winters still in the 2080s. Under both scenarios, the probability for unprecedentedly mild ice winters will increase during the study period.

Intermodel scatter around the median, 5th and 95th percentile was examined for the decade 2041-2050 to get an insight into the uncertainty caused by different climate models. For RCP8.5, there was a strong consensus among the model projections that the median MIB belongs to the class of mild ice winters in 2041-2050. Under RCP4.5 most of the models agreed with that. The scatter was widest for the 95th percentile under both scenarios: for most of the model projections, the high percentile belonged to the class of average ice winters. According to RCP8.5, severe ice winters will not occur anymore in the 2040s. The scatter was smallest around the 5th percentile: all model projections belong to the class of mild ice winters.

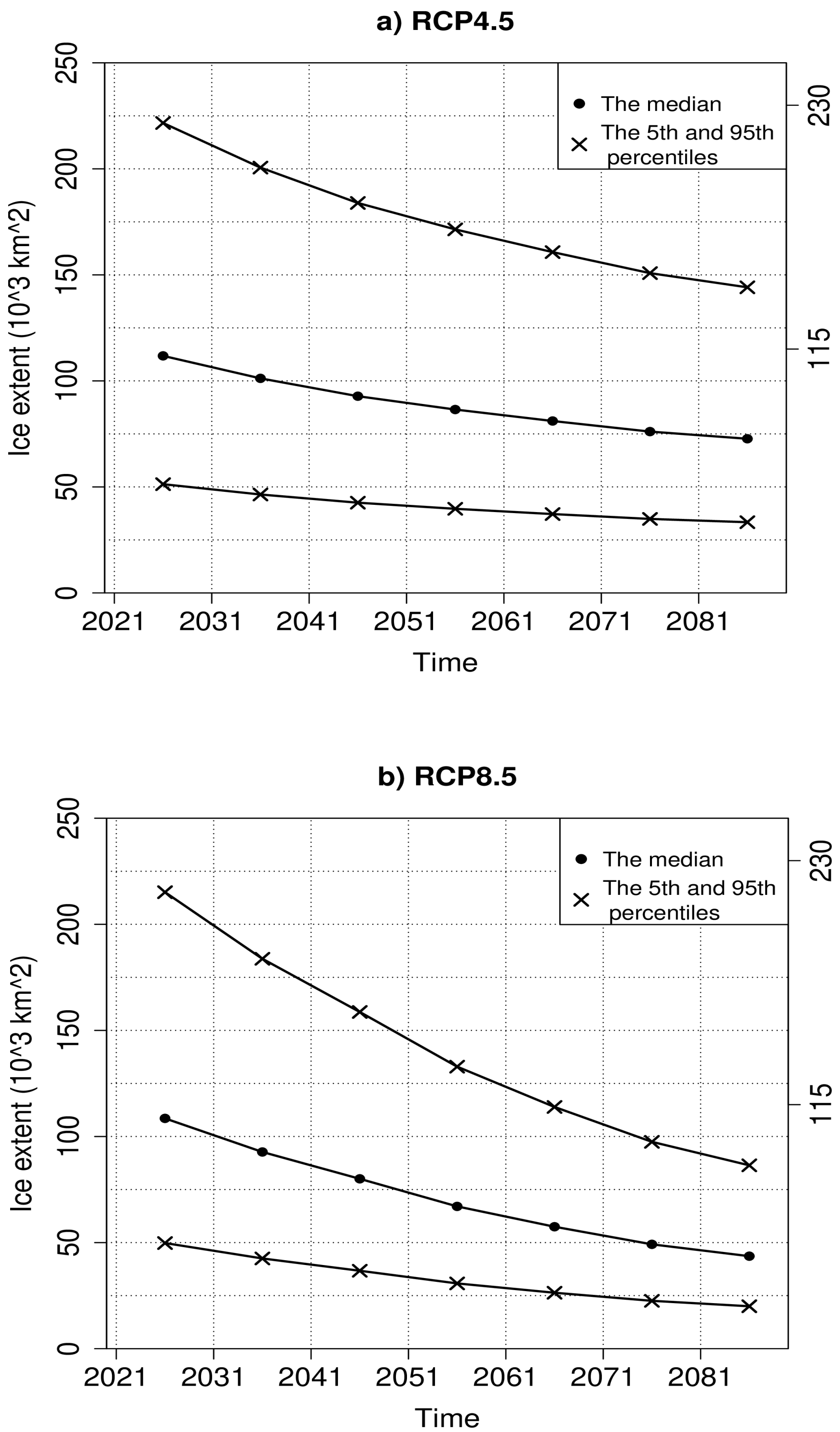

*Figure 9. Temporal evolution of the 28-model mean annual maximum ice extent in the coming decades according to a) RCP4.5 and b) RCP8.5. The vertical axis on the right shows the upper limits for mild and average ice winters. (Reproduced from Fig. 5 of **Paper III**.)*

5.2 Annual maximum fast ice thickness

Annual maximum fast ice thickness based on Eq. 2 was examined for two future decades, 2041-2050 and 2081-2090 as a response to the 28-model mean temperature projections. The ice thickness for the baseline period 1971-2000 was assessed using observed temperatures in Eq. 2. In the baseline period, most of the coastal areas become ice-covered in a typical contemporary winter (Fig. 10a). Still, there was a substantial variability in the ice thickness: in the Bay of Bothnia it was locally more than 90 cm, whereas in the southwestern parts of the Baltic Sea only 0-10 cm. The mean maximum ice thickness was projected to decrease in the coming decades according to both scenarios, but the decrease was faster under RCP8.5 scenario. Under RCP4.5, the ice thickness was projected to be about 60-80 cm in the Bay of Bothnia in 2041-2050 (Fig. 10b) and under RCP8.5 about 50-70 cm (Fig. 10c). In 2081-2090, the ice thickness in the Bay of Bothnia may locally still exceed 60 cm; elsewhere in the Gulf of Bothnia and in the Gulf of Finland, it is 10-40 cm, according to RCP4.5 (Fig. 10d). According to RCP8.5, most of the Baltic Sea will become ice-free in 2081-2090 (Fig. 10e). In the northernmost Bay of Bothnia ice thickness is still mainly 20-40 cm even if RCP8.5 is realized. Our results indicate that the Baltic Sea is unlikely to become totally ice-free in a typical winter during this century.

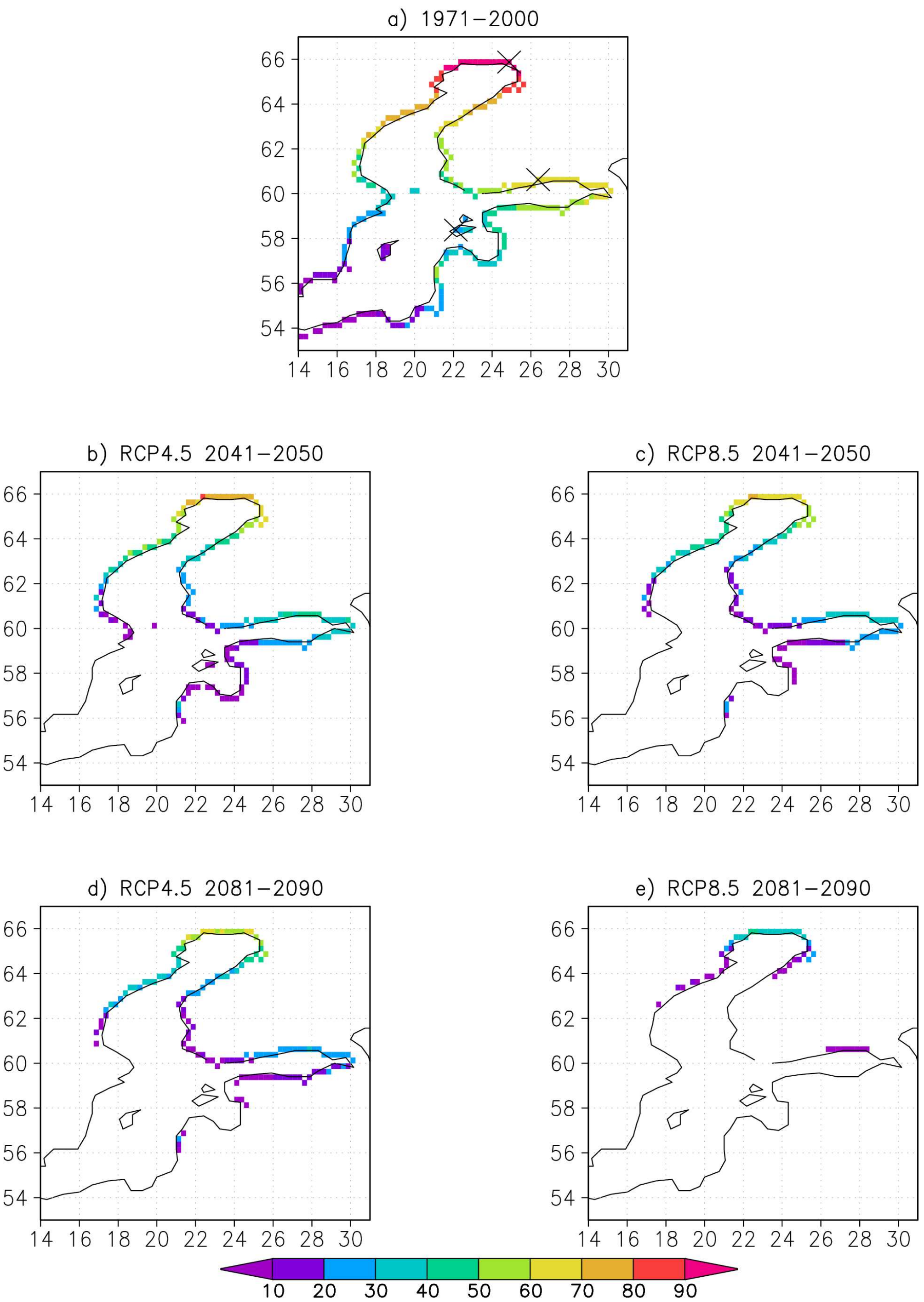

Fig. 10. The annual maximum fast ice thickness (cm) in the coastal regions of the Baltic Sea in a typical past and two future decade winters. The values are based on a) observed temperatures in 1971-2000 and b-e) the 28-model mean temperature projections under RCP4.5 and RCP8.5. (Reproduced from Fig. 8 of ***Paper III****.)*

The temporal evolution of ice thickness was examined separately at three locations, which are marked in Fig. 10a with crosses (Kemi, Loviisa and Vilsandi from north to south). The linear trends for Kemi and Loviisa, derived from the 28-model mean temperature responses, were about -3 cm/decade according to the RCP4.5 scenario and more than double under the RCP8.5. Relative to the period 1971-2000, the decline in 2041-2050 would be about 25-30% in Kemi and 40-50% in Loviisa (Table 1). At the most southern location, Vilsandi, there was little or no sea ice in a typical winter of the last three decades of the century, which made the trend notably weaker there than in Kemi or Loviisa. The disappearance of the ice cover in Vilsandi from the 2060s onwards does not, however, mean that sea ice cannot occur there at all in the late 21st century.

Table 1. The projected percentage reductions in the mean maximum ice thickness. The best estimates for the changes from the period 1971-2000 to future decades are based on the 28-model mean temperature projections. The 90% confidence intervals (given in parentheses) are derived from the inter-model differences in the temperature responses.

	Observation	RCP4.5		RCP8.5	
	1971-2000 (cm)	2041-2050 (%)	2081-2090 (%)	2041-2050 (%)	2081-2090 (%)
Kemi	75	25 (16-44)	37 (19-59)	32 (18-50)	63 (40-99)
Loviisa	38	40 (25-63)	57 (32-81)	50 (34-67)	83 (64-100)
Vilsandi		88 (46-100)	97 (81-100)	97 (80-100)	100

6. EXAMPLES OF NUMERICAL MODELING STUDIES IN CLIMATE RESEARCH

6.1 Performance of ECHAM5 in simulating snow melt timing

The snow-off date in ECHAM5 was analyzed first from the reference experiment (REF). Results of the experiment were compared to satellite observations (Fig. 11a) in all of Northern Eurasia. The comparison showed that the REF experiment (Fig. 11b) reproduced well the general pattern of snow-off dates that was seen in the satellite observations: the earliest snowmelt occurred in the Baltic Sea region (around julian day 80) and the latest in the Taymyr Peninsula (between days 150-160). However, in most of northern Eurasia, snow melted earlier in the model results than in the satellite observations, the difference being typically 5-20 days (Fig. 11c). On the other hand, in eastern Siberia and in some far eastern parts of Russia snow melted locally over 10 days later in REF experiment than in the satellite observations.

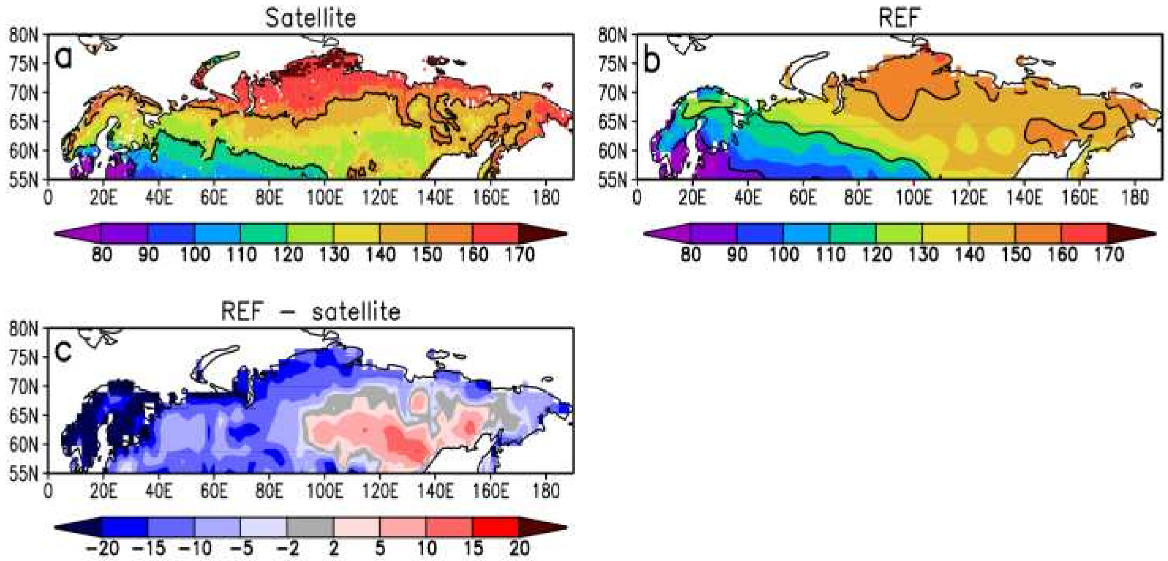

Figure 11. Mean snow-off date (SOD) in years 1979-2006 based on a) satellite retrievals and b) ECHAM5 REF experiment. Unit: Julian day. Snow-off dates of 90, 120 and 150 are indicated with black lines. c) The difference between b) and a). (Reproduced from Fig. 3 of ***Paper IV****.)*

To examine the possible reasons for the differences in snow-off dates we compared the temperature and surface albedo from REF simulation to observations. This comparison showed that in eastern Siberia, there were too high albedo values and too low temperatures and also too large accumulations of snow, whereas in the Taymyr region in spring, albedo values were underestimated and temperature overestimated and snow melted too early. The earlier than observed snow melt in western Russia and Scandinavia was due to too early start of snow melt. This occurs in spite of a slightly negative temperature bias in spring.

The sensitivity experiments, both nudging and different treatment of surface albedo, managed to reduce some of the model biases in snow-off date. Nudging made snow melt occur earlier in most northern Eurasia, with the largest effects (over 15 days) in southeastern Siberia and locally in Fennoscandia. In this region, the reason for earlier snow-off were higher temperatures and in eastern Siberia also slightly reduced snowfall. In northern parts of Northern Eurasia (e.g. Taymyr) and also in central Russia, snow-off was delayed. The changes in albedo parameterizations also made snow melt occur earlier in southeastern Siberia, and later in Taymyr and in a large area in central Russia and in Russian Far East. When nudging and albedo parameterizations were combined, the earlier snow melt in southeastern Siberia and later in Taymyr became even more pronounced. However, the early bias in snow melt in western parts of Northern Eurasia was not reduced considerably in any of the experiments. As this too early snow melt was accompanied by a negative bias in spring temperature, it implied that simulated temperature stays too low in the snow melt season. The main reason for this finding proved to be the simplifications in the calculations of surface energy budget: the surface energy budget was not computed separately for the snow-free and snow-covered parts of the grid cell. This means that the grid-mean surface temperature was not allowed to rise above 0°C, even if the snow-covered fraction was well below 1.

6.2 Sea-effect snowfall case on Finland’s west coast

On January 8, 2016, a record-breaking snowfall hit the west coast of Finland, in the municipality of Merikarvia, and accumulated 73 cm snowdrift in less than a day. On that day, all favorable conditions for cold-season convection (Jeworrek et al., 2017) were fulfilled. Due to the warm autumn, the Baltic Sea was still open, which enabled a long fetch over relatively warm water at the same time as cold arctic air masses reached the region.

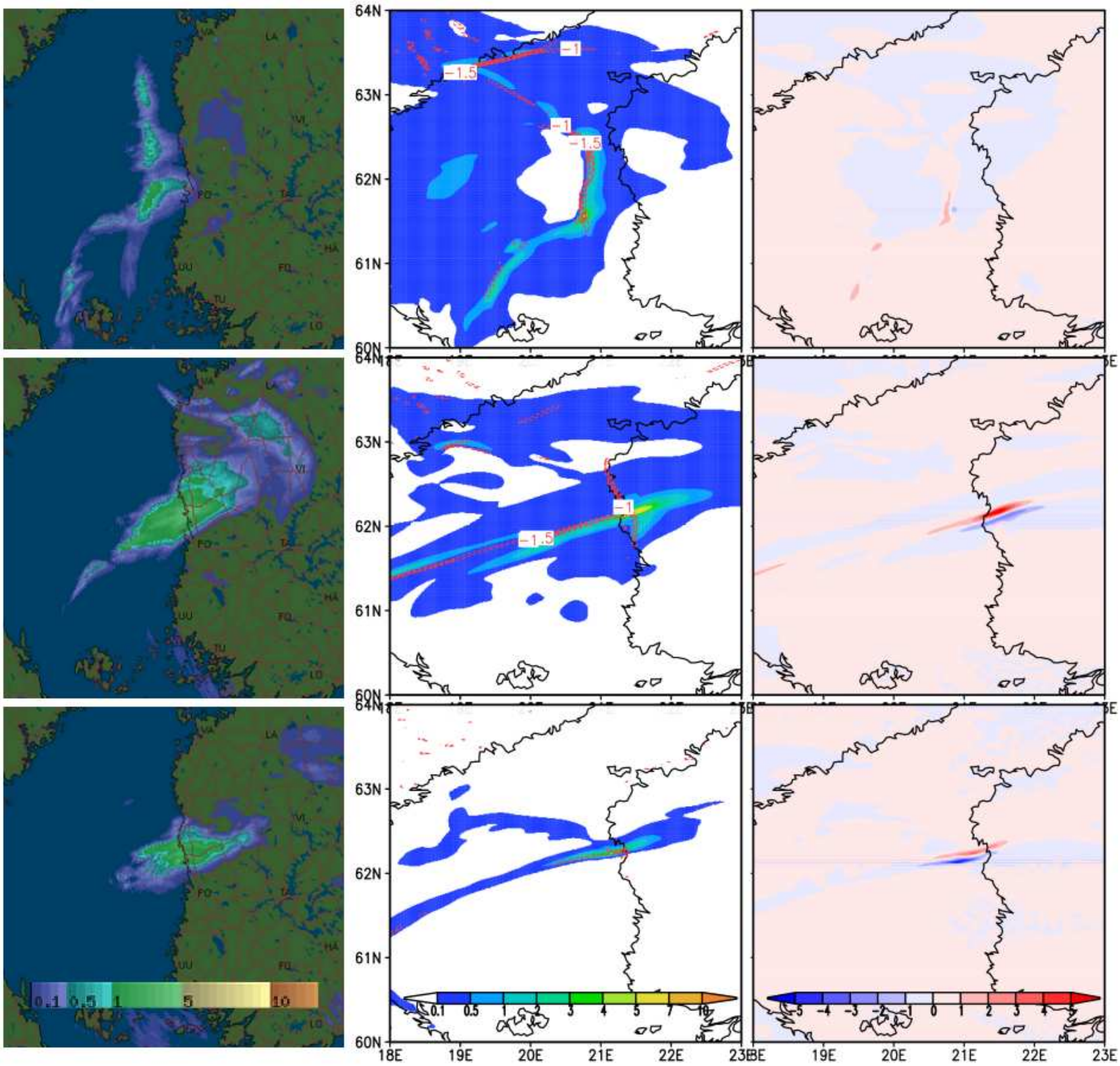

Figure 12. One-hour cumulative precipitation (mm/h) in the radar images (left panel) and forecast cycle 2016010803 at 05 (top), 13 (middle), and 21 (bottom) UTC on Jan 8 2016 simulated with HARMONIE with assimilated radar reflectivities (middle panel). Red contours show the simulated convergence zones. The difference between HARMONIE with and without assimilated radar reflectivities is shown in the right panel (mm/h). (Reproduced from Fig. 6 of ***Paper V****.)*

In **Paper V**, results from HARMONIE simulations of the snowfall case were compared to radar observations at 05, 13 and 21 UTC on January 8 (Fig. 12). At 05 UTC, the snowfall band was directed from south to north and was still located in the sea area offshore Merikarvia. At 13 UTC, the snowfall had intensified and was partly located over land areas and at 21 UTC, the snowfall area had become smaller and slightly weaker (Fig. 12, left column). When simulation results from the cycle that was initiated at 03 UTC on January 8 were qualitatively compared to radar observations, it showed that both HARMONIE simulations managed to capture the snowfall event. The assimilation of radar reflectivities (Fig. 12, middle column) spread the total area of simulated precipitation, produced a clearer hook to the coastline and the area of maximum precipitation grew slightly stronger. Radar assimilation especially intensified the precipitation more to the north when compared to simulation without radar assimilation. In Fig. 12, convergence zones are also shown. In these zones, near-surface winds converged, which further enhanced convective snowfall. When the results from other forecast cycles were compared with radar observations, it was found that the location of the snow band differed from the radar observations the most in the forecast cycles that were initiated 23-41 hours before the time of analysis. Also the simulated precipitation area was smaller than in later forecast cycles.

7. SUMMARY AND DISCUSSION

Knowing the prevailing climate conditions is relevant for society. As the global warming proceeds, it is crucial to understand that the global change affects the local conditions as well. Also for adaptation, the knowledge of the local scale conditions is needed. In this thesis, the main objective was to examine what the winters are like in Finland in the changing climate. In this section the research questions presented in section 1 are being answered.

- What kind of changes have occurred in snow conditions and factors affecting them in Finland?

This question was addressed in **Papers I** and **II**. The results from **Paper I** showed that snow depth has decreased and snow season shortened in large areas in Finland in 1961-2014. During this period, increasing precipitation and the changes in its composition had a significant role in observed changes in snow cover. In southern Finland, winters are becoming more rainfall-dominated. In northern Finland, the winter baseline temperature is still low enough that the increasing temperature has largely stayed below freezing. Thus, no clear change in snow cover occurred, even though increases in both solid and liquid precipitation were observed. In **Paper II**, the changes in the reindeer management area in northern Finland were analyzed for the years 1981-2010. The results were generally in agreement with the results of **Paper I**, but the strength of the trends were partly differing due to the shorter study period. This is an important fact to bear in mind when analysing trends: The selection of the time period always affects the results. Our findings of the changes in snow conditions are in line with those reported by Hannula (2012), Jylhä et al. (2014), Lehtonen (2015), Aalto et al. (2016), Lépy and Pasanen (2017) and Merkouriadi et al. (2017). The findings are also in line with the projections of the future snow conditions in northern Europe (Räisänen and Eklund, 2012; Räisänen, 2015).

- What kind of changes are expected to occur in sea ice conditions surrounding Finland?

In **Paper III**, the future changes in the Baltic Sea ice cover were assessed for 2020-2090 based on CMIP5 climate model simulations. The annual maximum ice extent in the Baltic Sea was found to decrease markedly under both RCP scenarios. According to RCP8.5, in practice only mild ice winters occur from the 2060s onwards. If the RCP4.5 is realized, the decline of the ice extent is slower and average ice winters may still occur even in the 2080s. Also the mean maximum sea ice thickness in coastal areas was found to decrease in the coming decades. According to RCP8.5, in the 2080s sea ice would occur only in the Bay of Bothnia with a maximum thickness of 30-40 cm. Based on RCP4.5, the coastal areas of the Gulf of Finland and the Gulf of Bothnia will still be ice-covered. Maximum ice thicknesses in the Bay of Bothnia would locally exceed 60 cm. Uncertainties in the results are largely due to the statistical calculation methods and the large spread among the individual models. On the other hand, the use of statistical methods enabled us to examine data from several climate models. The simple delta-change method that we used in constructing the future coastal temperatures assumed that the shape and width of the temperature distributions remained unchanged. In near-term temperature projections, this method is found to be a reasonable approach (Räisänen and Räty, 2013; Kämäräinen, 2013). For projections for the end of the century, a method including changes in the interannual variability would probably be beneficial. Despite the scatter in the rate of the future changes, the direction of the long-term trends is clear: sea-ice will significantly decrease, although the Baltic Sea is unlikely to become totally ice-free during this century.

The decreases in the ice-cover will have consequences on the ecosystems in the Baltic Sea. For example, the breeding habitats of the Baltic ringed seal will decline (Meier et al., 2004) or the timing of the spring bloom of phytoplankton will change (Eilola et al., 2013). On the other hand, shipping in the area will benefit from the longer ice-free period. As ice-free conditions become more common in wintertime, it may increase the number of sea-effect snowfall cases. This phenomenon is dependent also on other factors, which is why more research is needed of the favorable sea-effect snowfall circumstances in the future.

- What are the factors affecting climate model performance in simulating snow melt timing?

When climate model data is used, it is essential to understand that models have deficiencies. An example of these deficiencies was seen in our results in **Paper IV**, when the ability of ECHAM5 to describe the snow melt timing was evaluated. In general, ECHAM5 produced the observed geographical pattern of snow melt date quite well. Still, in some regions snow clearly melted too early and in some other regions too late. The biases that were found, were partly alleviated when nudging and surface albedo modification were used to correct the biases in simulated atmospheric circulation. Still, there were regional differences even after the albedo modifications and nudging. An important factor causing biases especially in the western parts of Northern Eurasia turned out to be too low a temperature in the snowmelt season, which resulted from simplifications in the model's surface energy budget.

It is worth noting that our results for performance concern only one model. Climate models with a more advanced snow and/or surface radiation scheme may perform differently. Thus, it would be beneficial to repeat these kinds of analyses with more advanced models. Overall, the results showed that many different processes affect the snow conditions in a climate model and improving a single process may either improve or deteriorate the agreement with observations. When climate models are used to predict future climate, it is thus important to use several models instead of just one and still regard the results with certain reservation. Continuous development of climate models is crucial for obtaining more reliable and accurate climate projections.

- How well can a sea-effect snowfall case be simulated over the Baltic Sea?

Paper V analyzed a sea-effect snowfall event which occurred on the west coast of Finland in 2016 causing a record-breaking snow depth increase of 73 cm in less than a day. High-resolution convection-permitting weather prediction model, HARMONIE, was used in the analysis with and without the assimilation of radar reflectivities. Both simulations managed to simulate the event quite well but assimilation of radar reflectivities improved the simulation results by spreading the most intense precipitation area and intensifying the precipitation more to the north. It was also found that the forecast cycles which were initiated closer to the event corresponded best with the radar observations in both simulations. However, these results were based on a qualitative assessment of a single sea-effect snowfall case. More cases need to be identified and analyzed to get a broader outlook of this phenomenon and to enable more accurate model predictions. This kind of small-scale heavy snowfall events may cause serious troubles for infrastructure near the coastline. Reliable prediction of such events is thus important for society as ice-free conditions become more common in wintertime.

Final remarks

Based on our results, some points arose that would be interesting to include in possible future studies.

- CMIP6 models are the newest generation of global climate models that are used to predict future climate conditions. How well are the snow conditions described in these models?
- When ice cover in the Baltic Sea decreases, it may affect the occurrence of sea-effect snowfall events. Further research is needed of the future conditions of these events.
- The gridded datasets, such as FMIClimGrid, will be available in higher resolution in the future. It would be interesting to examine more localized climate changes using, for example, 1 km resolution.
- There are many variables related to winter climate conditions that were excluded from this work. These include for example changes in the intensities of solid precipitation events and spatial changes in snow water equivalent.

It is obvious that winter climate conditions in Finland are changing and so far the changes have occurred more clearly in southern than in northern Finland. The need for high quality observations and data sets will most probably increase in the future when climate warming proceeds. Also improved climate and weather prediction models are necessary to produce more realistic climate projections which can help in considering possible impacts of the changes. The impacts of the changes can be very complicated and both beneficial and harmful even within the same region. For example, less snow in winter may decrease road maintenance costs but at the same time reduce wintertime outdoor recreation possibilities. For ecosystems, the strongest and most rapid impacts of climate change are expected in environments characterized by snow, ice and permafrost (Ministry of Agriculture and Forestry, 2014). When selecting the adaptation measures, it is thus important to assess all the relevant impacts in order to benefit from the positive effects and to reduce the adverse impacts. As the global warming continues, the importance of monitoring the climate conditions in the northern areas will amplify, which is shown in the findings presented in this thesis.

SUMMARIES OF THE ORIGINAL PUBLICATIONS

I **Luomaranta, A.**, Aalto, J. and Jylhä, K. (2019) Snow cover trends in Finland over 1961–2014 based on gridded snow depth observations, *International Journal of Climatology,* 39, 3147– 3159. https://doi.org/10.1002/joc.6007.

Paper I analyses the changes in monthly mean and annual maximum snow depth and several other snow-related indices in Finland during 1961-2014 using gridded observations of snow depth, temperature and precipitation. We found that snow depth has decreased and snow season has shortened in large areas in Finland. In Southern Finland the decrease in snow depth was driven by increasing mixed and liquid precipitation and, especially in spring, rising temperature. In Northern Finland, the decrease in snow depth was most evident in spring. In winter months, the solid precipitation was found to increase, but the increasing mixed and liquid precipitation and rising temperature likely counteracted the effect of increasing solid precipitation and thus we found no change in snow depth in winter months. The annual maximum snow depth was found to decrease in over 85% of Finland's area.

II Rasmus, S., Turunen, M., **Luomaranta, A.**, Kivinen, S., Jylhä, K. and Räihä, J. (2019) Climate change and reindeer management in Finland: co-analysis of practitioners knowledge and meteorological data for better adaptation, *Science of the Total Environment*, 710, 136229, https://doi.org/10.1016/j.scitotenv.2019.136229.

In **Paper II**, the interannual variability and changes in selected temperature-, precipitation- and snow-related indices in 1981-2010 in Northern Finland's reindeer management area were analyzed using gridded observation data. The results from the analysis were examined together with knowledge from reindeer herders, which was gathered via a survey questionnaire. The found climatic changes in the gridded data were generally consistent with earlier studies. The practitioner experiential knowledge was mainly in line with the results from meteorological observations.

III **Luomaranta, A.**, Ruosteenoja, K., Jylhä, K., Gregow, H., Haapala, J. and Laaksonen, A. (2014) Multimodel estimates of the changes in the Baltic Sea ice cover during the present century *Tellus A*, 66, 22617, http://dx.doi.org/10.3402/tellusa.v66.22617.

Paper III examines the changes in the annual maximum ice extent and the maximum coastal fast ice thickness in the Baltic Sea during the ongoing century. A non-linear regression model was fitted to coastal temperatures and annual maximum ice extent data for the years 1952-2012 and this regression model was then used together with CMIP5 climate model data to predict the maximum ice extents in the coming decades. According to both RCP scenarios studied, the annual maximum ice extent was found to decrease markedly. Under the RCP8.5 scenario, virtually only mild ice winters occur from the 2060s onwards. Under RCP4.5, the decline of the ice extent is slower: average ice winters may still occur even in the 2080s. For assessing the coastal fast ice thickness an analytical solution based on the sum of freezing-degree days was used. According to RCP8.5, in a conventional winter of the 2080s, sea ice would only occur in the Bay of Bothnia, with a maximum ice thickness of 30-40 cm, and in the north-eastern parts of the Gulf of Finland, with an ice thickness of 0-10 cm. According to RCP4.5, the coastal areas of the Gulf of Bothnia and the Gulf of Finland will still be ice-covered in the 2080s.

IV Räisänen, P., **Luomaranta, A.**, Järvinen, H., Takala, M., Jylhä, K., Bulygina, O. N., Riihelä, A., Laaksonen, A., Koskinen, J. and Pulliainen, J. (2014) Evaluation of North Eurasian snow-off dates in the ECHAM5.4 atmospheric general circulation model, *Geoscientific Model Development*, 7, 3037-3057, https://doi.org/10.5194/gmd-7-3037-2014.

Paper IV evaluates the timing of spring-time snow-off in Northern Eurasia in the ECHAM5 atmospheric GCM using satellite observations as reference data. In southeastern Siberia and in far eastern parts of Russia, snow was found to melt too late in the ECHAM5 simulations whereas in the western parts and Taymyr region snow melt occurred too early. Several sensitivity experiments with ECHAM5 were conducted where found biases were corrected through nudging and/or modifying the treatment of surface albedo. The results from sensitivity experiments led to the conclusion that the treatment of surface energy budget in the model was one of the main reasons for the differences between observed and modeled snow-off.

V Olsson, T., Post, P., Rannat, K., Keernik, H., Perttula, T., **Luomaranta, A.**, Jylhä, K., Kivi, R. and Voormansik, T. (2018) Sea-effect snowfall case in the Baltic Sea region analysed by reanalysis, remote sensing data and convection-permitting mesoscale modelling, *Geophysica*, 53(1), 65-91.

Paper V analyses a strong small-scale sea-effect snowfall case in Merikarvia, Finland, which led to a new national record-breaking snowdrift of 73 cm. The event was investigated using ERA5 reanalysis data, the Global Navigation Satellite System (GNSS) and the numerical weather prediction model HARMONIE with and without assimilation of observed radar reflectivities. HARMONIE simulated the intensity of the snowfall situation well but the spatial spread of the snowfall remained too narrow. Assimilation of radar reflectivities improved the simulation results by increasing the moisture content of the boundary layer and by spreading the most intense precipitation area. The results showed that the combination of these three methods can help in obtaining the best possible insight into local severe weather events.

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